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ON THE ACCURACY OF CONTOUR CHARTS IN FORECASTING UPPER WINDS

By R. MURRAY, M.A.

Summary.—The practical importance of the various errors associated with forecasting winds by means of contour and forecast contour charts is assessed for the 700-, 500-, 300- and 200-mb. levels.

Isobaric charts contain errors in terms of wind arising from the following factors: (i) errors caused by inaccuracy of contour-height observations, (ii) errors caused by inaccurate estimation of geostrophic wind, (iii) errors owing to the personal element in chart construction, (iv) wind-measurement errors, (v) small-scale wind fluctuations and (vi) geostrophic departures. Most of these errors are acceptably small, but (i) increases in importance with height and becomes the largest individual error at 200 mb. These errors are inherent in the contour method of wind representation and cannot be substantially reduced, except at high levels where an increase in the accuracy of contour-height observations is required.

In forecasts there is an additional error because of erroneous forecasting of contour patterns. In 24-hr. forecasts of wind at a point this is the main cause of forecast errors up to 300 mb., but at 200 mb. it is about equal to the combined effect of errors inherent in the contour method.

Introduction.—The established method of forecasting upper winds is by measuring geostrophic values on forecast contour charts (prontours) for selected isobaric surfaces, extrapolating and interpolating as necessary. The method introduces several sources of error in addition to the obvious error which arises from erroneous forecasting of the contour patterns. By examining the British aerological data and upper air isobaric charts for the 700-, 500-, 300- and 200-mb. levels for April 1950, an attempt has been made to estimate the overall standard error and to analyse this according to the different contributory factors. The analysis is mainly concerned with forecast errors at a point in space and time; but it must be remembered that the errors associated with forecasting mean winds over a route or an area or a period are substantially smaller, and, furthermore, that such mean winds are more important than point winds for most practical purposes.

The various errors, which limit the value of contour charts as a means of representing the wind flow, are assessed and discussed, and additional errors arising from forecast contour charts are dealt with. The main results (in terms of root-mean-square errors and variations) are then stated.

Accuracy of contour charts in representing upper winds.—The accuracy with which contour charts can be used in practice to represent the upper wind field depends on several factors which are assessed in the following subsections.

Errors due to inaccuracy in observations of height.—Sheppard[1]* has examined the errors of heights of isobaric surfaces in British radio-sonde observations.

* The index numbers refer to the bibliography on p. 11.

From his work it is estimated that the standard height errors are about 20, 30, 70 and 100 ft. at 700, 500, 300, and 200 mb. respectively. There are additional systematic errors rather larger than these casual errors, but the systematic errors affect all stations in the same aerological network equally at the same time and are not relevant to the present problem.

It is not easy to estimate how much the errors of upper air temperature observations (i.e. height errors) contribute in fact to the errors of height gradients (geostrophic winds) on constructed charts. Where observations are numerous the analyst can minimize the errors by smoothing; where observations are widely scattered the entire field must be interpolated and a small error in observation is relatively unimportant. Over the British Isles the aerological network is sufficiently dense to define the field fairly definitely, but not so dense as to permit much smoothing.

However, an assessment can be attempted by assuming that the geostrophic wind at the centre of a square of side l is derived from four radio-sonde observations at the corners of the square. Then the standard vector error in the geostrophic wind is $g\varepsilon\sqrt{2}/\lambda l$, where g is the acceleration of gravity, λ is the Coriolis parameter and ε is the standard error of contour height. Using values appropriate to the British Isles, where the upper air stations are about 200 miles apart, estimates of the standard vector errors of geostrophic wind caused by errors in height are obtained as shown in Table I.

TABLE I—ESTIMATED ROOT-MEAN-SQUARE VECTOR ERRORS OF GEOSTROPHIC WIND CAUSED BY HEIGHT ERRORS

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square vector error of geostrophic wind	3	4	10	14

The figures given in Table I can only be rough estimates, but they are considered reasonably accurate. It will be observed that the error is small at lower levels, but increases to the relatively large value of 14 kt. at 200 mb.

Errors due to estimation of geostrophic wind.—The measurement of geostrophic wind at a definite point from a contour chart is not entirely an objective process. The contours are height isopleths often far apart, they are curved and non-parallel, etc., and in practice the analyst allows for the variations as seems best to him on the basis of synoptic judgment.

A test was carried out in which two analysts made independent measurements of geostrophic wind on the same charts (183 comparisons were made). The root-mean-square vector difference between the two sets of measurements was 8·7 kt. for a sample of observations with mean wind speed equal to about 40 kt. This implies that the root-mean-square vector error associated with measuring geostrophic wind is about 6 kt., i.e. $8{\cdot}7/\sqrt{2}$ kt. Broadly speaking the geostrophic measurement error increases with the contour gradient, so that on the average larger errors occur at 300 mb. than at 700 mb. By allowing for the different mean wind speeds of the test samples given in Table VII, the geostrophic measurement errors are estimated in Table II. It is difficult to see how these errors can be reduced to any considerable extent.

TABLE II—ROOT-MEAN-SQUARE VECTOR ERRORS PRODUCED BY INACCURACY IN ESTIMATION OF GEOSTROPHIC WIND

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square vector error of measured geostrophic wind	5	7	8	6

Errors due to personal element in chart construction.—Two analysts using the same basic observations will undoubtedly construct somewhat different charts. The estimated " personal errors " are given in Table III. They are the result of a comparison of geostrophic measurements made on a set of upper air charts drawn at the Central Forecasting Office, Dunstable, with geostrophic measurements on a similar set constructed independently at London Airport, due allowance being made for the errors of measurement of geostrophic wind given in Table II.

TABLE III—ROOT-MEAN-SQUARE VECTOR ERRORS IN GEOSTROPHIC WINDS ARISING PURELY FROM THE PERSONAL FACTOR IN CHART CONSTRUCTION

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Personal root-mean-square vector error ..	4	5	6	4

In the neighbourhood of the British Isles, the similarity of the two sets of charts on visual inspection is very striking. The differences are mainly minor, and Table III shows that the " personal errors " are acceptably small.

Wind errors.—In the British network upper winds are measured at land stations by GL. Mk III radar equipment and on ocean weather ships by 277 P radar equipment. Errors in wind arise from basic radar observational errors. Bannon[2] and Harrison[3] have discussed the errors of wind observations made at British land stations and on ocean weather ships respectively. The estimates of the wind errors given in Table IV are based on their results, taking account of the proportion of land and ship observations in the sample used in this investigation.

TABLE IV—ROOT-MEAN-SQUARE VECTOR ERRORS OF WIND MEASUREMENT

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square wind error	2	3	4	4

The wind errors listed in Table IV are acceptably small in synoptic work. The wind errors of British land stations are about half the values given in Table IV, whilst the wind errors of ships are perhaps two or three times greater than the figures given. On the whole wind errors at British stations are negligible, except perhaps for observations of strong wind made at sea.

Small-scale fluctuations.—Turbulent wind fluctuations, which cannot be determined from the contour pattern, occur in the free atmosphere. The very small fluctuations tend to be smoothed out in the process of obtaining " observed wind ", which is in fact a mean wind over a layer of the atmosphere during an interval of two or three minutes. From a consideration of observational data contained in papers by Durst[4], Durst and Gilbert[5], and Loeser[6], an estimate has been made of the order of magnitude of the wind fluctuations which are too large to be smoothed out in obtaining " observed winds " yet too small to be represented in the contour pattern. The figures given in Table V are thought to be, if anything, slight over-estimates.

TABLE V—ROOT-MEAN-SQUARE VECTOR ERRORS CAUSED BY SMALL-SCALE FLUCTUATIONS

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square vector error of small-scale fluctuations	4	4	4	4

The figures given in Table V are manifestly quite small, and nothing can be done to make allowance for them in synoptic work.

Overall errors inherent in technique.—Comparisons of wind with height gradient, quite apart from the inadequacy of the geostrophic approximation, must contain errors caused by the combined effect of the errors enumerated above. On the assumption that these errors are independent so that their mean squares are additive, overall inherent technique errors given in Table VI are readily obtained.

TABLE VI—OVERALL INHERENT ROOT-MEAN-SQUARE VECTOR ERRORS AFFECTING COMPARISONS BETWEEN CONTOUR GRADIENT AND WIND

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Overall inherent root-mean-square vector error	8	11	15	16

With the exception of wind errors these overall errors are inherent in the contour-chart technique, because of inaccuracies of analysis, observations and geostrophic wind measurements; they do not include the additional error caused by the non-fulfilment of the theoretical geostrophic relationship. The omission of wind errors from Table VI does not materially affect the figures.

It cannot be said that the overall inherent technique errors given in Table VI are negligibly small, particularly at 300 and 200 mb. Some reduction in the overall errors at high levels would result from an improvement in the accuracy of the basic temperature observations, since the largest of the individual errors discussed above arises at 300 and 200 mb. from contour-height errors (see Table I); otherwise it is difficult to see how these basic errors can be decreased to any great extent.

Apparent departure from geostrophic value on working charts.—A set of working charts drawn at the Central Forecasting Office, Dunstable, were copied, omitting all basic observations. The figures given in Table VII result from a comparison of observed winds with measured geostrophic winds on these replica working charts.

TABLE VII—ROOT-MEAN-SQUARE APPARENT GEOSTROPHIC DEPARTURE ON WORKING CHARTS

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square geostrophic departure ..	10	14	20	18

The apparent geostrophic departures (i.e. magnitudes of the vector difference between observed wind and measured geostrophic wind) indicate the disagreement between wind and contour gradient produced by the limitations both of the charting technique and of the geostrophic approximation. Charts forecast exactly, that is identical with subsequently drawn " actual " charts, are likely to contain root-mean-square vector errors in terms of wind of about the magnitude indicated in Table VII. The statistical data show that on about 50 per cent. of the occasions the apparent geostrophic departures are less than 9 kt. at 700 mb., 11 kt. at 500 mb., 16 kt. at 300 mb., and 14 kt. at 200 mb.

It is interesting to note that at each isobaric level the speed (or line) and angular (or cross-wind) departures are approximately equal—actually the root-mean-square speed departures were about 1 kt. greater than the cross-wind effects.

Geostrophic departures.—The figures given in Table VIII are estimated root-mean-square geostrophic departures, obtained by subtraction (square root of difference of squares) of the figures in Table VI from those in Table VII, on the assumption that the apparent geostrophic departures are a combination of real departures with errors inherent in the technique.

TABLE VIII—ESTIMATED ROOT-MEAN-SQUARE GEOSTROPHIC DEPARTURES

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square geostrophic departure ..	6	9	13	8

It will be noted that the geostrophic departures given in Table VIII are rather less than the overall errors of technique given in Table VI.

Recent investigations by Neiburger, Sherman, Kellogg and Gustafson[7], Bannon[8], Godson[9], Hartmann[10] and Durst and Gilbert[5], employing different data and techniques, show that geostrophic departures are in general of the order of 10 kt. in the lower and middle troposphere—broadly in agreement with the estimates in the present work.

Furthermore, Neiburger, Sherman, Kellogg and Gustafson[7] examined the value of the " gradient wind " approximation, and came to the conclusion that it is not significantly better than the simple geostrophic approximation in practice. Godson[9] also found that the cross isobaric wind component, which is assumed to be zero in estimates of both geostrophic and gradient wind, is on the average almost of the same magnitude as the deviation of geostrophic wind speed from actual wind speed. Much earlier Sutcliffe[11] demonstrated theoretically that such results might be expected, since the cyclostrophic component is only one of several factors associated with a lack of balance between wind and pressure gradient. However, there is no satisfactory method available for direct measurement of non-geostrophic winds on contour charts, although perhaps on some occasions a dynamical appreciation may allow a qualitative estimate to be made.

Accuracy of 24-hr. forecast contour charts.—Upper air forecast contour charts are prepared twice daily at the Central Forecasting Office, Dunstable (based mainly on aerological data for 0300 and 1500 G.M.T.) ; these charts attempt to depict the contour patterns about 24 hr. after the time of the basic observations. In April 1950, the period examined in this investigation, forecast contour charts for 200 mb. were not prepared at the Central Forecasting Office, although such charts have since become part of the routine issue. It was therefore necessary to prepare a set of 200-mb. forecast contour charts (60 charts) for April 1950, simulating forecasting conditions as much as possible. Tests were made of the accuracy of these forecast contour charts (for 700, 500, 300 and 200 mb.) by comparing forecast winds (obtained by geostrophic measurement) with the subsequently observed winds at Larkhill, Lerwick, station I (59°N. 19°W.), and at station J (52½°N. 20°W.). When observed winds were missing no comparisons could be made ; also, on a few occasions with winds available, comparisons were not utilized in the statistics when the 24-hr. vector wind change could not be computed, since it is desirable to compare the forecast error with the wind change. A test was also made of the wind error associated with forecasting the mean wind over a 1,200-mile route running from west to east at 55°N., i.e. more or less in the middle of the British aerological network.

Accuracy of 24-hr. wind forecasts at a point.—The results of the comparison between forecast (geostrophic) winds and observed winds, together with the 24-hr. wind variations and " percentage success " are contained in Table IX. The " percentage success " has been suggested by Priestley[12] as a measure of forecasting success: it is the percentage of the 24-hr. wind variation successfully forecast and is given by the expression $100\ \{(v^2-e^2)/v^2\}^{1/2}$, where e is the root-mean-square forecast error and v is the root-mean-square 24-hr. wind variation.

It will be observed from Table IX that the root-mean-square forecast errors are greatest at 300 mb., where the wind speed and wind variations are generally greatest. Nevertheless the percentage success is also greatest at this level ; it appears that large changes can usually be forecast better than small changes. Incidentally, the frequency distributions of the individual errors at each level show that roughly 70 per cent. of the errors were equal to or less than the root-mean-square forecast errors ; while forecast errors greater than twice the root-mean-square forecast errors occurred on from 3 to 5 per cent. of occasions.

TABLE IX—ROOT-MEAN-SQUARE 24-HR. FORECAST ERRORS AND WIND VARIATIONS AND " PERCENTAGE SUCCESS "

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
Root-mean-square forecast error (kt.) ..	20	27	33	25
Root-mean-square wind variation (kt.) ..	25	35	48	27
" Percentage success "	60	64	73	38
Number of comparisons	218	218	185	167

The 24-hr. wind variation at 200 mb. shown in Table IX is less than the long-period normal variation for April. This is a real effect, and is not caused mainly by some strong winds being missing from the comparisons; for an examination of the standard vector deviations from the 200-mb. monthly mean winds at Larkhill for April 1948, 1949 and 1950 shows not only that there is a good deal of variability from year to year, but also that the wind variability in April 1950 was about 10 kt. below the long-period normal. The subnormal 200-mb. wind variation does not materially affect the general results here, except in so far as it probably makes the percentage success at 200 mb. smaller than it would otherwise be.

It is clear that the root-mean-square forecast errors at all levels are considerably larger than any of the individual sources of errors listed in Tables I to VIII (remembering that the squares of root-mean-square values are compared in considering the relative importance of individual factors). These forecast errors include contributions from the apparent geostrophic departures (i.e. overall inherent errors together with geostrophic departures) as well as from incorrect forecasting of the contour patterns. The magnitudes of the errors arising purely from erroneous forecasting of the contour patterns are approximately assessed in Table X by subtraction of the apparent geostrophic departures (Table VII) from the forecast errors (Table IX).

TABLE X—ROOT-MEAN-SQUARE ERRORS DUE TO ERRONEOUS FORECASTING OF THE CONTOURS (REAL FORECASTING ERROR)

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square real forecasting error ..	17	23	26	17

Clearly the errors arising from erroneous forecasting of the contour patterns (or the real forecasting errors) are substantially less than the total forecast errors (which comprise the real forecasting errors together with the apparent geostrophic departures). Nevertheless, the real forecasting errors account for the major part of the total forecast errors up to 300 mb.; it appears that at 200 mb. the real forecasting error is about the same magnitude as the apparent geostrophic departure (comprising errors of observation, technique and the geostrophic approximation).

Accuracy of 24-hr. forecasts of mean wind over a 1,200-mile route.—It is well known that the errors associated with forecasting mean winds over routes are less than those which occur in point forecasts, and that the errors decrease with increasing length of the routes. The sort of improvement to be expected has been assessed by evaluating the mean wind (geostrophic) over the 1,200-mile route from 55°N. 25°W. to 55°N. 5°E. on both actual and forecast charts at 700 and 200 mb. for April 1950. The root-mean-square vector errors in 24-hr. forecasts of mean wind are actually about 13 kt. at 700 mb. and 17 kt. at 200 mb.

Durst[13] has shown that the standard vector deviation of mean wind for a 1,200-mile route is about 0·76 times the average standard vector deviation of points along the route. On the assumption that the root-mean-square vector error in mean wind forecasts for a 1,200-mile route also falls off at the same rate as the standard deviation of the wind to be forecast, it is estimated that the root-mean-square vector error in forecasting mean winds over the 1,200-mile route is 0·76 times the root-mean-square 24-hr. forecast error for point forecasts; thus, using the values contained in Table IX, the root-mean-square vector errors of forecast mean wind are likely to be about 15 kt. (i.e. 0·76 × 20) at 700 mb., 21 kt. at 500 mb., 26 kt. at 300 mb. and 19 kt. at 200 mb. The observed root-mean-square vector errors of forecast mean wind over the 1,200-mile route concerned are actually 13 kt. at 700 mb. and 17 kt. at 200 mb., that is, 2 kt. less than the estimated values. It is probable that the root-mean-square errors of forecast mean wind at 500 mb. and 300 mb. are also some 2 kt. smaller than the values estimated, and they are therefore taken as shown in Table XI.

TABLE XI—ROOT-MEAN-SQUARE VECTOR ERRORS OF 24-HR. FORECASTS OF MEAN WIND OVER A 1,200-MILE ROUTE

	Pressure level			
	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
Root-mean-square 24-hr. forecast error ..	13	19	24	17

The errors given in Table XI may be compared with the errors associated with point forecasts (see Table IX). It is estimated that these root-mean-square vector errors of 24-hr. forecasts of mean wind could be reduced by 5–10 kt. if the errors associated with erroneous forecasting of the contour patterns could be eliminated; then further reduction would occur only by dealing with the geostrophic departures and inherent technique and analysis errors.

Conclusions.—The errors associated with the use of contour charts in forecasting upper winds near the British Isles have been shown to contain contributions from errors which may be regarded as fundamental to the technique, the analysis and the basic observations. The main results are presented as root-mean-square vector errors or variations or departures in Table XII, based on the trial period. Row (12) contains the standard vector deviations from the seasonal mean wind, obtained from *Geophysical Memoirs* No. 85[14]; these figures give an idea of the errors likely to occur if the seasonal mean wind were to be used as a forecast wind. It should be remembered that, roughly, the relative importance of the entries in Table XII is proportional to their squares.

TABLE XII—MAGNITUDE OF ERRORS IN 24-HR. FORECASTS OF WIND (AT A POINT) FROM FORECAST CHARTS ANALYSED ACCORDING TO THE CONTRIBUTION OF VARIOUS FACTORS AND COMPARED WITH THE VARIABILITY OF THE WIND AT SELECTED LEVELS

All figures are root-mean-square vector errors or departures or variations

	700 mb.	500 mb.	300 mb.	200 mb.
	knots			
(1) Error owing to errors of observations of contour height	3	4	10	14
(2) Error produced by inaccurate estimation of geostrophic wind	5	7	8	6
(3) Error arising from personal element in chart construction	4	5	6	4
(4) Error in measurement of wind*	2	3	4	4
(5) Error caused by small-scale fluctuations	4	4	4	4
(6) Overall inherent technique error* (errors (1) to (5) combined)	8	11	15	16
(7) Apparent departure from geostrophic value on working charts	10	14	20	18
(8) Geostrophic departure (error (7) less (6))	6	9	13	8
(9) 24-hr. forecast error	20	27	33	25
(10) Error caused by erroneous forecasting of contours (error (9) less (7))	17	23	26	17
(11) 24-hr. wind variation	25	35	48	27
(12) Standard vector deviation from seasonal mean wind	28	36	50	40

* Errors in wind measurement affect any comparison between forecast and observed winds and are therefore included here. They should not strictly be regarded as part of the forecast error, but their omission does not materially affect the figures in row (6).

The main conclusions from this study are :—

(i) A considerable contribution to the errors of forecasting upper winds by the contour technique is made by errors inherent in the technique, which cannot, by any obvious means, be avoided.

(ii) Errors in the wind observations are negligibly small (except perhaps with strong winds at ocean weather ships).

(iii) Errors in the temperature observations (i.e. contour-height errors) become significant at 300 mb. and serious at 200 mb. Indeed at 200 mb. this error is overwhelmingly the largest contribution amongst the various factors given in entries (1) to (5) of Table XII.

(iv) Errors owing to geostrophic departures account for only a rather small fraction (of the order of ten per cent.) of the total root-mean-square error of forecasts. The geostrophic approximation must therefore be regarded as reasonably satisfactory in practical work on upper wind forecasting by contour methods.

(v) Errors caused by the erroneous forecasting of the contour patterns are definitely the greatest up to 300 mb. at least, accounting for some 70 per cent. of the total forecast error at 700 and 500 mb. and about 60 per cent. at 300 mb. At 200 mb. this error is about equal to the combined effect of errors of observation and technique. Thus there is considerable scope for improvement of the wind forecasts by attacking the problem of improving the forecast contour charts, even without tackling the question of the apparent geostrophic departures (i.e. real geostrophic departures, observation and technique errors).

(vi) The total forecast errors are substantially less than the 24-hr. wind variations except at 200 mb. where the difference is small. However, the errors due to erroneous forecasting of the contour patterns at all levels are much less than the 24-hr. wind variations.

(vii) As was expected, the errors associated with forecasting mean winds over long routes (the type of forecast of most importance in practice) are considerably less than the wind errors of point forecasts.

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